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Patentanmeldung Nr. | Patent application No. | Demande de brevet n°

98200454.1

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The Innas Fork Lift Truck

Working under Constant Pressure

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1 Introduction

The Dutch engineering company Innas BV has developed a Free Piston Engine which is intended to be used as the prime mover in hydrostatically driven mobile machinery. Because of its better efficiency, its smaller number of parts and its higher power to weight ratio, this Innas Free Piston Engine or IFPE can be a strong competitor to conventional diesel hydraulic power units.
The advantages of the IFPE are exploited fully if it can be designed for operation at a constant or slightly varying output pressure.
Consequently, when using the IFPE in a vehicle, a constant pressure rail from which the wheel drive, the implement systems and the auxiliary functions take their power, is the obvious choice.

The resulting type of hydraulic circuit layout is often referred to as being 'secondary controlled': the vehicle functions are controlled at the secondary side, directly at the energy users. The hydraulic power unit is controlled in such a way that it keeps the rail pressure above a minimum level.
In contrast to this, the more conventional type of hydraulic circuit layout is generally called primary controlled. Here, the flow from the power unit is controlled to produce the desired speed of the vehicle functions.

The Innas fork lift truck is based on an existing representative of the lightest category of diesel powered fork lift trucks. In this category, installed engine power is typically 30 kW.
The vehicle's building phase started in May 1997, its maiden drive was planned for the beginning of November 1997.

The major goal for the Innas fork lift truck is to serve as a test platform to explore the design and operational issues associated with this kind of IFPE- and IHT based, constant pressure mobile machinery drive line.
This paper focuses on the first experiences gathered in this way. The way the main functions of the fork lift truck have been incorporated in the testbed design is described and the chosen vehicle control strategy is presented.
First however, a brief introduction to the operating principles of IFPE and IHT is given, as they represent the two key components for this design, but are relatively new to the field of hydraulic technology.

2 The Innas Free Piston Engine

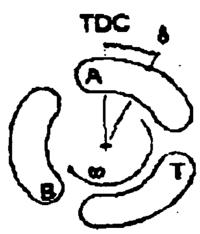
Figure 1 shows a simplified scheme of the IFPE. The heart of the engine consists of a hydraulic plunger, to which a piston is rigidly connected. As the plunger moves back and forth, the piston engages in a two stroke, loop scavenged diesel process. The plunger has two parts, each of them moving in a different hydraulic cylinder. The part moving in the compression cylinder is essentially a piston with differential areas. When both sides of this piston are supplied with the pressure from the compression accumulator, a force in the direction of the Top Dead Centre (TDC) results. This force propels plunger and piston towards the TDC, thereby compressing the air in the combustion cylinder. During this movement, oil flows out of the compression accumulator. When the piston moves back from TDC to the Bottom Dead Centre (BDC), roughly the same amount of oil flows back. The compression accumulator can be seen as the equivalent to the flywheel in conventional combustion engines.
The part of the plunger that moves in the pump cylinder acts as a simple plunger, pumping oil from the low pressure to the high pressure side of the IFPE.
The high and low pressure accumulators are necessary to damp the pulsations resulting from the block shaped flow pattern.

3 The Innas Hydraulic Transformer

In this context, the description of the operating principle of the IHT can only be limited. In /5/ an extensive discussion of the IHT can be found.

The IHT in its current design is based on a bent axis axial piston hydrostatic motor. The main difference to a normal bent axis unit is in the port plate. The standard pump or motor port plate has two port kidneys, fixed in their circumferential position relative to the TDC of the axial piston movement. The IHT port plate has three kidneys, each one connected to the environment through ports in the transformer's end cap. The port plate can be rotated around its central axis in order to change the position of the kidneys with respect to the TDC of axial piston movement, thereby altering the ratio of the flows through the ports.
The axle of the bent axis unit is not used. The power in the IHT is transferred from the oil in the A-port, through the pistons underneath this port, the swashplate and the pistons underneath the B-port, to the oil in that port.

In figure 2, a top view of the new port plate is sketched. In this view, the barrel with cylinders would run below the paper, its rotational direction is indicated in the figure. The TDC mark refers to the point were the pistons reach their topmost position.



A: connected to the constant pressure rail
B: connected to the load
T: connected to low pressure or tank
TDC: *point were the pistons reach their Top Dead Centre*
δ: port plate control angle
ω: rotational speed of transformer

Figure 2: Port plate of an axial piston type IHT

For first quadrant operation, the situation drawn, the A-kidney of the IHT might be referred to as the motoring kidney. The net flow through this kidney is directed into the IHT. The cylinder volumes underneath this kidney are expanding.
The B-kidney might be called the pumping kidney, as the net flow through this kidney is directed out of the IHT. The cylinder volumes underneath are compressing.
The ratio of A- and B-kidney flows is fully determined by the port plate geometry and the selected port plate angle δ.

4 The wheel driv system

In fork lift trucks in the 30 kW class, the rear wheels are steered and the front wheels are driven. The wheel drive system is laid out in such a way that a continuous differential function between the driven wheels is realised. Because these fork lift trucks are predominantly used on hard, flat terrain, no lock up is required.
Control of the wheel drive system in this class of fork lift trucks, is always automatic, as may be expected in a vehicle were the driving direction is constantly changed and the driver's attention is mainly required for the moving and positioning of goods. Taking these typical characteristics as the goal to meet, a constant pressure hydrostatic wheel drive system can still be realised in different ways. For the Innas fork lift truck, after evaluating and rejecting several other possibilities /6/, the two drive line options presented in figure 4 were examined in more detail.

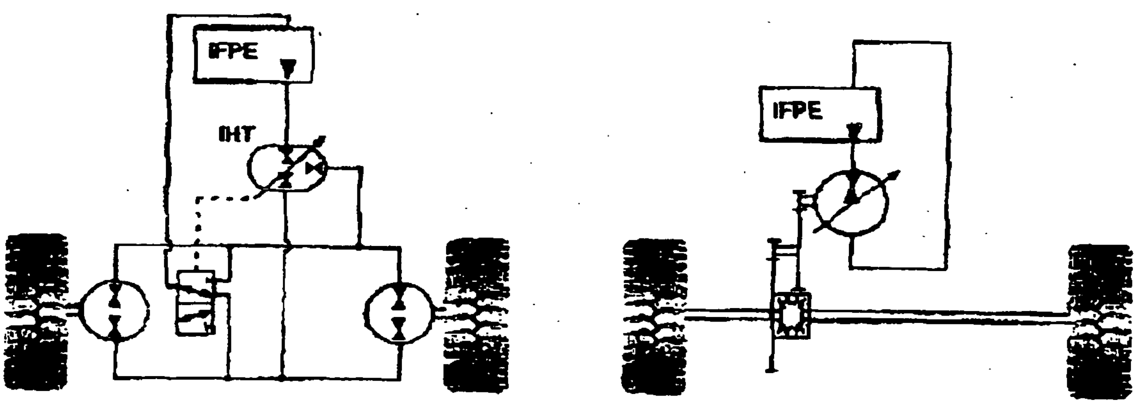


Figure 4: The two most interesting wheel drive options

The first option consists of one IHT controlling the pressure to two constant displacement radial hydrostatic motors. By connecting them in parallel, the required differential function is realised. The second option uses a secondary controlled variable hydromotor to drive the pinion of a differential gear in a standard drive axle.

The main item of comparison is the drive line efficiency. In order to judge both options on this aspect, the efficiencies of the components between pressure rail and wheels may be compared. For a typical field of wheel torques and speeds, the efficiency maps of figure 5 can be calculated.
The maps show that the layout with the variable motor displays a better efficiency at low speeds and high wheel torques. In a large field of operation however, the

The prototype is based on an existing hydrostatic fork lift truck. Only its carrying structure, its wheel hub motors and its lifting - and steering cylinders were retained. The conventional hydraulic power unit and the rest of the hydraulic circuitry were removed.
In order to be able to deliver maximum drive torque, the wheel hub motors require a maximum pressure of 420 bar. Because the IFPE is operated as a constant pressure system at 300 bar, the drive IHT has to be able to amplify this pressure as well.
The drive IHT was designed and built taking a commercially available 45 cc hydromotor as its base unit.

The need for the 3/2-valve in the wheel drive circuit (figure 4) originates from the requirement for four quadrant operation of the wheel drive system.
This can best be explained by looking at the transformer's flow balance when operating in the first quadrant. As can be seen in figure 3, when turning the transformers port plate to transform its B-port pressure to the desired value, the B-port flow generally does not match the T-port flow.
The B-port flow passes the hydrostatic drive motors and is fed back into the line connected to the T-port. The difference between this flow and the T-port flow presents an excess flow which has to be returned to the low pressure accumulator.
For four quadrant operation, it should be possible to switch the high and low pressure sides of the drive motors. For the IHT this simply means controlling the port plate angle over zero. With this, the low pressure connection should switch over to the non pressurised side of the wheel drive circuit.
The 3/2-valve can be switched in accordance with the pressure situation in the wheel drive system or when the port plate moves over zero. The latter option has been chosen for the fork lift truck.

The IFPE and wheel drive IHT in this secondary controlled wheel drive circuit almost present a drop-in replacement of the internal combustion engine (ICE) and the attached variable pump in a conventional wheel drive circuit.
For these two combinations (conventional ICE with variable pump and IFPE with IHT), a comparison of costs and weight has been made, based on realistic projections for IFPE's and IHT's, when produced in similar series as the conventional engine and pump.

F r the Innas Fork Lift Truck the implement control is initially solved in a far more simple and less costly way: by governing the port plate angle in open loop.
Of course, this means accepting that the load disturbance rejection is poor. This is considered acceptable, as for the fork lift truck the only load disturbance which is likely to happen is the fork meeting the load, after moving some distance without resistance. If the fork would slow down or even stop in this situation, this would not feel wrong to the driver. He would simply do the natural thing and increase the port plate angle to continue lifting the fork.
Another possible load disturbance could be the load falling off the fork. In that - far less likely - case the fork should not accelerate to very high speeds. To prevent this from happening, flow limiting valves can be incorporated in the system.

Based on this reasoning, it was decided to realise the lift and tilt circuit without speed control. This results in the hydraulic system presented in figure 6.

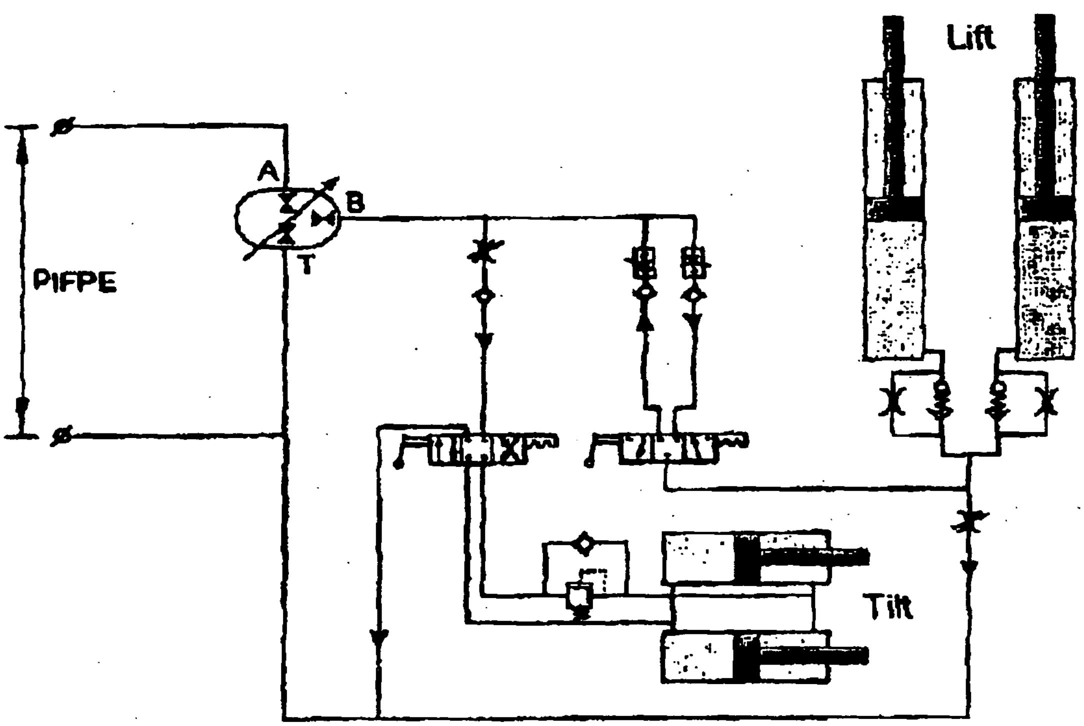


Figure 6: The lift and tilt circuit

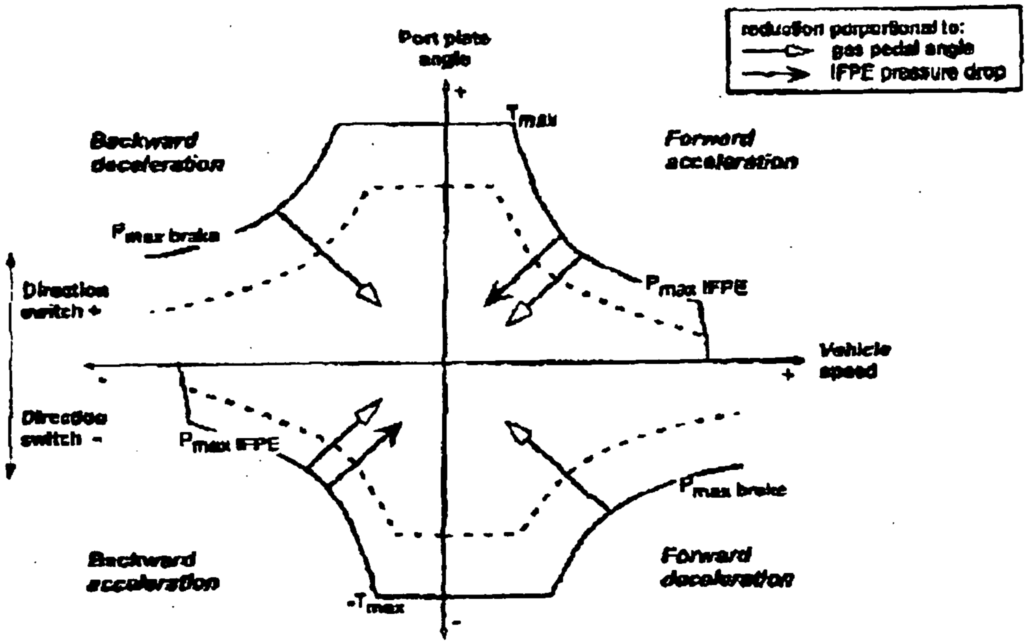


Figure 7: Drive control strategy

In the acceleration quadrants also a possible power shortage should be avoided. If maximum power is required from the wheel drive system and control calculations do not match physical circumstances, it is possible that the total amount of power consumed by the wheel drive system exceeds the installed IFPE power. The same can happen when other hydraulic systems in the lift truck are used and the total power required for those functions and the driving process is larger than the installed power. In those circumstances, maintaining the control strategy described above could result in choking the engine.
In the Innas fork lift truck this situation can be resolved in a very simple way: demanding more power then the IFPE can deliver immediately expresses itself in a pressure drop in the high pressure accumulator. This pressure is available in the IFPE control unit. By reducing the port plate angle of the drive IHT proportional to the pressure drop, the power used by the drive system is reduced until the total amount of power, matches what the IFPE can provide.
In other words: every power conflict is resolved by reducing the power to the wheel drive process. Because in the fork lift truck the total power required by the other vehicle functions does never exceed the installed IFPE power, no power limiting control is required for the other vehicle functions.

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ABSTRACT

The invention relates to a hydrostatic fork lift truck having wheel hub motors, lifting and steering cylinders and a hydraulic engine connected to the wheel hub motors via a wheel drive circuit. The hydraulic engine is a free piston engine and the truck is equipped with a hydraulic transformer for providing the required pressure to the free piston engine.